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Thermal Environment, Ammonia Concentrations, and Ammonia Emissions of Aviary Houses with White Laying Hens

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THERMAL ENVIRONMENT, AMMONIA CONCENTRATIONS, AND AMMONIA EMISSIONS OF AVIARY HOUSES WITH WHITE LAYING HENS

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ABSTRACT. *Maintaining comfortable thermal environments and good indoor air quality is essential to ensuring optimal production performance, welfare, and health of animals. Alternative laying-hen housing systems are being adopted by some egg producers in the U.S. However, information on indoor thermal and aerial environments of such alternative housing systems is meager. This article reports a one-year monitoring of thermal conditions (air temperature and relative humidity or RH) and ammonia (NH_3) concentrations and emissions of four aviary laying-hen houses (same dimensions, manure belt plus litter floor systems, 50,000-hen capacity each) at a commercial farm in the Midwest U.S. Carbon dioxide (CO_2) concentrations at the air inlet and near the exhaust fans were measured and used, along with literature values of the metabolic rates of the hens, to estimate building ventilation rate (VR). The results show that indoor temperature, RH, CO_2 concentration, NH_3 concentration, and VR of the four houses (mean ±standard deviation) were 23.4°C ±0.3°C, 64% ±3%, 1520 ±87 ppm, 5.2 ±0.4 ppm, and 4.5 ±0.6 $m^3\ h^{-1}\ hen^{-1}$, respectively. The highest daily mean NH_3 concentration was 13 ppm (and 20 ppm within the day) in winter. The NH_3 emission rate was 0.14 ±0.01 g $d^{-1}\ hen^{-1}$. These values of NH_3 concentrations and emissions were lower than those reported for European aviary houses. The NH_3 emissions of the monitored aviary houses in this study are comparable to those of U.S. manure-belt cage houses, but are much lower than those of U.S. high-rise cage houses. The magnitude of NH_3 emissions observed in this study was consistent with that of similar aviary houses with brown hens in another extended field measurement in the same region.*

Keywords. *Air pollutants, Ammonia, Concentration, Emission, Laying hen.*

In livestock production, ammonia (NH_3) is produced during degradation of urea and uric acid in animal manure and urine. Exposure to high NH_3 concentrations can be detrimental to the farmer's health and depresses production performance of the animals (Crook et al., 1991; Deaton et al., 1984; Xin et al., 2011). Ammonia emissions to the atmosphere are well recognized for their acidification and eutrophication effects on ecosystems (Asman et al., 1998). As estimated by the U.S. EPA, the majority of the anthropogenic (man-made) NH_3 emissions are from livestock production (USEPA, 2004a). A number of studies have been or are being conducted to acquire baseline NH_3 emission data for U.S. animal feeding operations, covering cattle (Harper et al., 2009), swine (Jacobson et al., 2011; Stinn et al., 2012), and poultry production facilities (Liang et al., 2005; Wheeler et al., 2006; Li et al., 2011; Moore et al., 2011). These data will help to improve the U.S. national gaseous emission inventory and provide a benchmark for developing realistic abatement plans and strategies.

Estimation of NH_3 emissions from laying-hen houses by the U.S. EPA is based on the conventional cage housing systems (USEPA, 2004b). In recent years, alternative hen housing systems have been increasingly used by some egg producers to meet niche market needs. Aviary system is an alternative housing system that features lower hen stocking density and daytime litter floor access, which allows the hens to perform their natural behaviors, such as dust-bathing and foraging. While part of the hen's manure, i.e., the portion that is collected on the manure belts under the colony tiers, is removed frequently from the house (e.g., every 1 to 4 days), the manure on the litter floor remains in the house until the end of the production cycle (about one year). This manure accumulation on the floor results in higher NH_3 volatilization as compared to conventional manure-belt cage systems.

Ammonia concentrations and emissions of aviary houses have been measured in Europe (table 1). The results

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Table 1. Summary of ammonia (NH_3) concentrations and emissions reported for European aviary hen houses.

NH_3 Conc. (ppm)	NH_3 Emission (g d^{-1} hen^{-1})	Manure Removal Frequency	Manure/Litter Drying	Litter Floor Access	Reference
6	0.30	2 times/week	Manure on belt	All day	Groot Koerkamp (1995)
0.7 to 3.3	0.02 to 0.10	5 to 7 times/week	Litter	All day	Groot Koerkamp et al. (1998b)
0.8 to 16	0.05 to 0.62	2 times/week	No drying	All day	Groot Koerkamp and Bleijenberg (1998)
32 to 38	0.78	1 time/week	-	-	Nimmermark et al. (2009)
20 to 35	-	1 time/week	-	-	Winter et al. (2009)
35 to 60	-	No removal	-	-	Winter et al. (2009)
12.7 to 15.5	0.35 to 0.46	1 to 2 times/week	Manure on belt	8.3 to 11 h d^{-1}[a]	Dekker et al. (2011)

[a] Includes litter floor and outdoor access. The house was an organic free-range system.

indicated that NH_3 concentrations and emissions vary largely within and between studies. The large variations are probably due to different manure and litter handling practices (e.g., frequency of belt manure removal, manure moisture content, and hours of hen access to the litter floor per day). Therefore, direct extrapolation of the European data to U.S. aviary systems may be inappropriate. Baseline data on NH_3 concentrations and emissions for U.S. aviary housing systems are thus needed.

The objective of this study was to monitor NH_3 concentrations and emissions of representative U.S. commercial aviary laying-hen houses over a one-year period. Concentrations of carbon dioxide (CO_2) were monitored concurrently for estimating house ventilation rate (VR) based on the CO_2 mass balance method, thus calculating NH_3 emissions. In addition, air temperature and relative humidity (RH) were continuously measured for both the ambient and indoor environments throughout the experimental period.

Materials and Methods

Aviary Hen Houses

A commercial egg farm with six double-wide aviary hen buildings located in central Iowa was selected as the experimental site. Each double-wide building had a solid partition wall that divided it into two symmetrical houses. Each house measured 150.8 × 21.4 × 3.0 m (L × W × H) and had a housing capacity of 50,000 hens, which were distributed in six rows of colonies (fig. 1). The colony rows were divided by wire mesh screens into ten 13.5 m sections along the length. The litter floor measured 6.0 m wide for the two inner aisles and 3.0 m wide for the two outer aisles. Measurements were carried out in four such houses (or two double buildings).

Fresh air entered the houses through continuous eave inlets to the attics and then through ceiling box air inlets. Twenty exhaust fans, including four 0.6 m diameter variable-speed fans, four 0.9 m diameter single-speed fans, and twelve 1.3 m diameter single-speed fans were installed

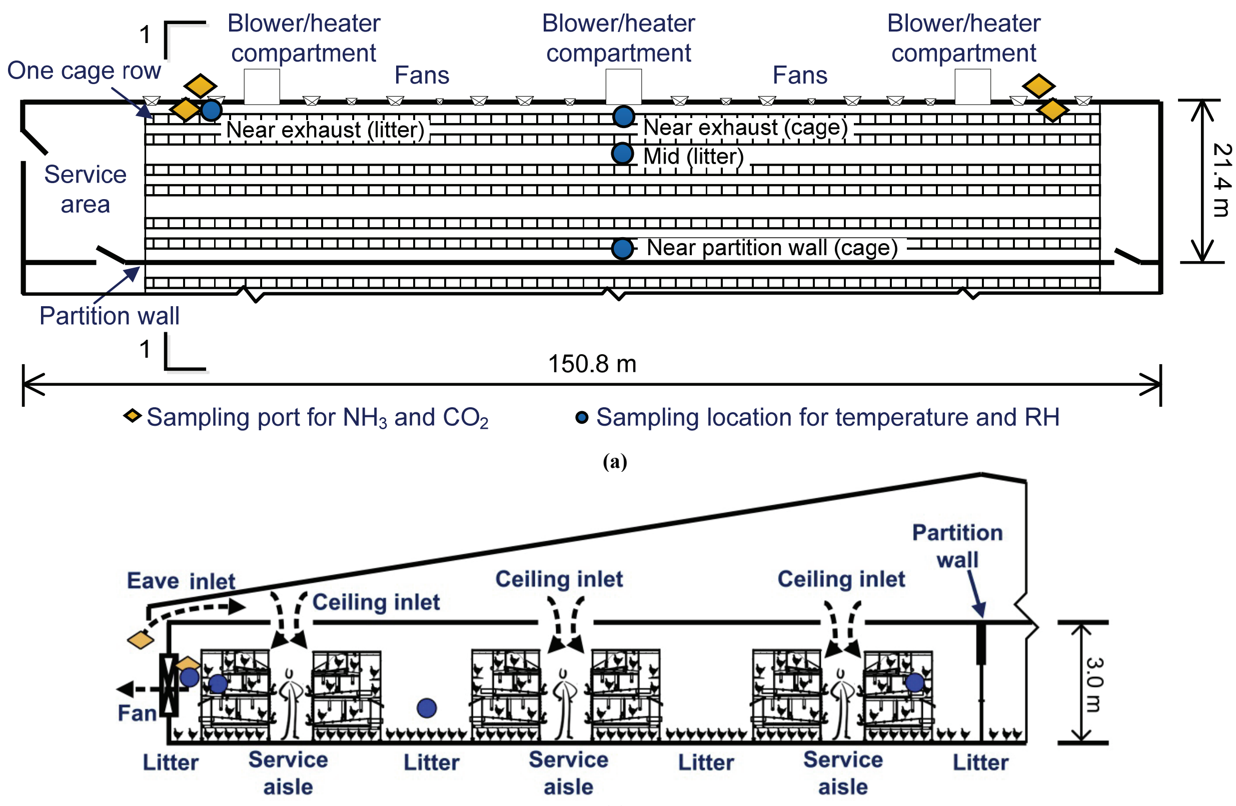


Figure 1. (a) Floor plan and (b) cross-section 1-1 of the aviary laying-hen house, showing indoor sampling locations for ammonia (NH_3) concentration, carbon dioxide (CO_2) concentration, temperature, and relative humidity (RH) measurements.

in the sidewall of each house. The four 0.6 m fans ran continuously at their maximal capacity, and the rest of the fans were controlled to be on or off in an effort to maintain the indoor temperature between 20°C and 25°C. The maximum design ventilation capacity was 12.2 $m^3 h^{-1} hen^{-1}$ (at static pressure of 12.4 Pa), and the minimum ventilation rate was 0.5 $m^3 h^{-1} hen^{-1}$.

One blower and one 73.25 kW gas-fired forced-air heater (model AD250, L.B. White Co., Onalaska, Wisc.) were installed in each of the three blower/heater compartments attached to the house (fig. 1). The blowers continuously delivered the air in the compartment (recirculated room air) to the room through the perforated air ducts below the colony cages and above the manure belts. The gas heaters were turned on to heat the compartment air when the indoor temperature fell below 18°C and off when the temperature of the compartment reached 47°C (a safety control) or the house temperature reached its setpoint. When operating at maximal capacity, each heater consumed 10.7 L h^{-1} liquid propane gas (LPG). This blowing/heating setup was conducive to drying the manure on the belts, which reduced NH_3 volatilization, and achieving even distribution of the supplemental heat throughout the house.

The aviary hen colony cages were equipped with nest boxes, perches, feeders, and nipple drinkers (fig. 2). Specific resource allowances are listed in table 2.

Table 2. Resource allowance of the aviary house.

Parameter	Value
Wire mesh floor space	620 $cm^2 hen^{-1}$
Litter floor space	510 $cm^2 hen^{-1}$
Nest space	80 $cm^2 hen^{-1}$
Perch space	13 cm hen^{-1}
Feeder space[a]	7-10 cm hen^{-1}
Nipple drinker	8.6 hens $drinker^{-1}$

[a] 7 cm hen^{-1} is based on the absolute feeder length, and 10 cm hen^{-1}1 is based on feeders inside the colonies being accessible on both sides.

HENS AND MANAGEMENT PRACTICES

Lohmann SL white hens were brought into the houses at 17 weeks of age and were kept in the colonies (i.e., no access to litter floor) until 22 weeks of age. From then until the end of the production cycle (at 67 to 78 weeks of age, depending on management decisions), the hens were given litter floor access for 9.75 h a day (12:00 p.m. to 9:45 p.m.). In the morning, lights came on gradually starting at 5:00 a.m., and reaching the maximum level at 6:00 a.m. In the evening, lights were dimmed down starting at 8:45 p.m. and were completely off at 9:45 p.m. The gradual transition of lighting levels was to simulate sunrise and sunset. The manure belts were run at 6:00 a.m. for 10 min each morning so that manure on one-third of the manure belt length was removed from the houses.

MEASUREMENTS

The field monitoring was carried out from 30 August 2011 to 30 August 2012. The ages of hens at onset of the monitoring were 47, 39, 51, and 46 weeks in houses 1, 2, 3, and 4, respectively. All the houses had flock changes during the monitoring period (fig. 3). During the two-week downtime (i.e., time between the old and new flocks), the litter on the floor was completely removed, and the house was cleaned with compressed air. No measurement was made during the downtime.

Ambient and indoor concentrations of NH_3 and CO_2 were measured for two consecutive days every two weeks with Portable Monitoring Units (PMUs). Each PMU had two electrochemical NH_3 loggers (0 to 200 ±1 ppm, model PAC III; Draeger Safety, Inc., Pittsburgh, Pa.) and one infrared CO_2 transmitter (0 to 5,000 or 0 to 7,000 ±20 ppm, model GMT222, Vaisala, Inc., Woburn, Mass.). With its three-way

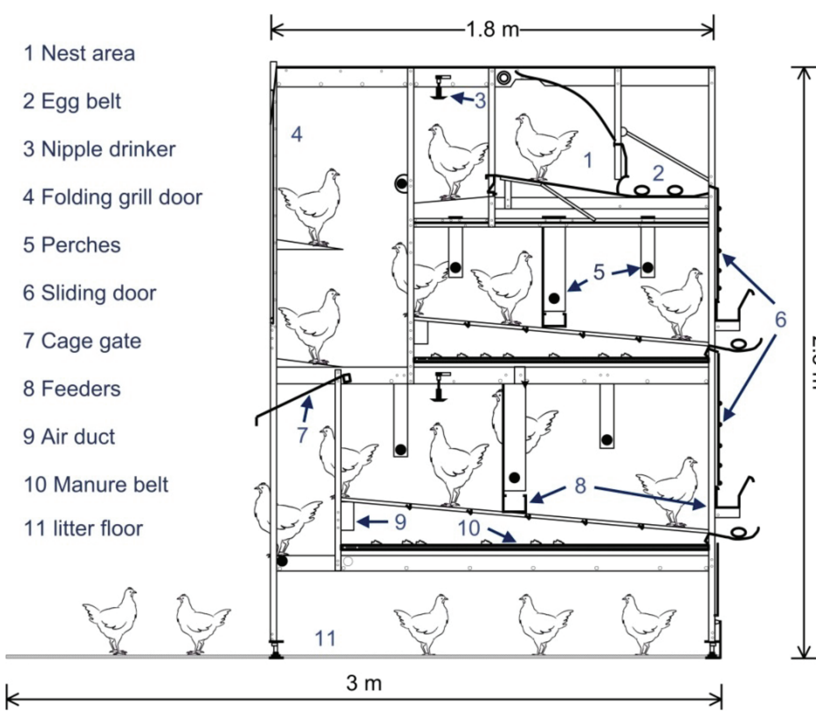


Figure 2. Cross-sectional view of the aviary colony with litter floor.

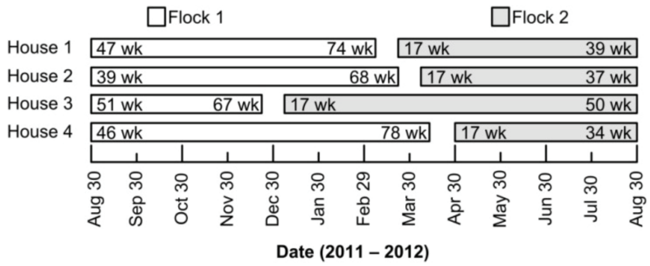


Figure 3. Hen age during the monitoring period (30 Aug. 2011 to 30 Aug. 2012).

time-controlled valve, the PMU measured both ambient and indoor gas concentrations in a cyclic manner. This feature helped to purge the NH_3 sensors with fresh ambient air prior to sampling the indoor NH_3-laden air, thereby avoiding sensor saturation. A detailed description of the PMU design and operation was given by Xin et al. (2003). In this study, two PMUs were installed in each house and programmed to cycle between 20 min sampling of ambient air and 10 min sampling of indoor air, yielding 30 min interval data. The NH_3 and CO_2 concentrations were recorded every 30 s during the two-day sampling events. Considering the response time of the sampling system, only the last 2 min of data of the 20 and 10 min sampling in each cycle were used to determine the NH_3 and CO_2 concentrations at the sampling moment. By processing the raw data as mentioned above, the ambient and indoor concentration data were staggered by 10 or 20 min. To align the ambient and indoor sampling time for gas emission calculation, the ambient concentration corresponding to the indoor sampling moment was calculated using linear interpolation between two consecutive ambient sampling moments (30 min interval). The two indoor sampling ports were near the continuous exhaust fans, and the two ambient sampling ports were installed next to the eave air inlet (fig. 1).

Temperature and RH (HOBO Pro Series, Onset, Bourne, Mass.) were continuously measured at 5 min intervals with portable data loggers at different indoor locations and two outside locations (fig. 1). In houses 1 and 2, the indoor measurement locations were "above litter area near exhaust", "in colony cage near exhaust", "above middle litter area", and "in colony cage near partition wall". For houses 3 and 4, temperature and RH were measured only at the latter three locations. Ambient temperature and RH were measured nearby house 1 and house 3 with the same type of T/RH loggers. To prevent solar radiation/irradiation, the loggers for ambient measurement were protected in perforated plastic cylinders.

QUALITY ASSURANCE AND QUALITY CONTROL

Prior to each sampling episode, a two-point check or calibration (if necessary) was performed on the NH_3 loggers and CO_2 transmitters with zero gas (ultra-high pure nitrogen, 99.999%, Praxair, Danbury, Conn.) and span gas (27 ppm for NH_3 or 3100 ppm for CO_2, Praxair, Danbury, Conn.). After calibration (if needed), the sensors were challenged with reference gases of the same concentrations. If the reading of an NH_3 logger differed from the reference gas concentration by 2 ppm or more, the logger was recalibrated until it passed the challenge test. The same procedures were followed for the CO_2 transmitters whose readings were within 20 ppm when challenged with the zero gas or within 2% (62 ppm) when challenged with the span gas.

The NH_3 loggers are relatively vulnerable to the sampling environments in livestock houses; thus, they can lose accuracy over time. To ensure acceptable performance of the loggers, they were subject to another challenge after each sampling episode. If the reading of an NH_3 logger was not within the acceptable range (±2 ppm of the reference gas concentration), the data collected with that particular logger were excluded from further data analysis.

The temperature and RH loggers (purchased new for the study) were checked and calibrated prior to the field monitoring and again in the middle of the monitoring period. A final check of these loggers was done after the one-year monitoring period.

CALCULATION OF VENTILATION RATE AND EMISSIONS

Building ventilation rate (VR) of the hen houses was determined indirectly using the CO_2 mass balance method that has been proven to be relatively accurate and cost-effective as compared to direct ventilation measurement (Li et al., 2005; Mosquera et al., 2012). This method calculates VR by dividing the total CO_2 production rate in the house by the difference of indoor and ambient CO_2 concentrations (eq. 1). VR determined with the CO_2-balance method becomes unreliable when indoor CO_2 concentration is close to ambient level (ΔCO_2 < 200 ppm) (Li et al., 2005). In that case, VR was either set to the maximum ventilation capacity when indoor temperature was higher than the setpoint for the highest fan stage, or was excluded from calculation when the operation of all ventilation fans became uncertain. It should be noted that during hot days (when outside temperature exceeded 32°C), the producer purposely lowered the house temperature setpoint by 5.5°C to 7.2°C to increase fan runtime at night.

In aviary houses, CO_2 is produced from four sources: the hens' metabolism or respiration, litter/manure on the floor, manure on the belts, and fuel combustion when the gas heaters are in operation. Production of CO_2 by the hens was calculated based on the hens' body weight and their bioenergetics values, i.e., specific total heat production rate (THP) and respiratory quotient (RQ), as reported by Chepete et al. (2004). The THP and RQ were set to be 7.5 W kg^{-1} and 0.89 during the day and 5.6 W kg^{-1} and 0.93 at night (eq. 2). Production of CO_2 by the litter/manure on the floor was measured with a static flux chamber, as used by Hayes et al. (2013a). The data showed that CO_2 production by the litter floor was linearly related to the litter thickness: 0.0315 mL s^{-1} m^{-2} per cm of litter depth, or 90.4 mL s^{-1} $house^{-1}$ per cm of litter depth (litter area of 2871 m^2 per house). Starting from 22 weeks of age, the increase of litter thickness was estimated to be 0.12 cm $week^{-1}$, derived from field measurements. For the CO_2 production by manure on the belts, an empirical value of 1% of the hens' respiration was used (Ning, 2008; Hayes et al., 2013a). This empirical value was based on 1/3 of the belt manure being removed each day, so the CO_2 was produced from 1/3 belt manure being 0 to 1 day old, 1/3 being 0 to 2 days old, and 1/3 being 0 to 3 days old. In winter, the runtime of the heaters was estimated based on the temperature elevation (measured by a HOBO temperature sensor) in the blower/heater compartments, and using ambient and indoor temperatures as secondary check. The CO_2 production by one 73.15 kW heater was estimated to be 968 mL s^{-1} (Ni et al., 2008; Zhao et al., 2013). On days without supplemental heating and at 3.36 cm litter thickness (50 weeks of age), the daily mean CO_2 production rate was calculated to be 0.458 mL s^{-1} hen^{-1}, which is nearly identical to the value of 0.459 mL s^{-1} hen^{-1} (20°C, RQ = 0.91) predicted by CIGR (Mosquera et al., 2012).

$$\mathrm{VR} = \frac{n \cdot P_{hen} + P_{litter} + P_{manure} + P_{heater}}{n \cdot \left([\mathrm{CO_2}]_{in} - [\mathrm{CO_2}]_{amb}\right)} \times 3600 \tag{1}$$

where

VR = ventilation rate (m^3 h^{-1} hen^{-1})
n = number of hens in a house
P_{hen} = CO_2 production by hen (mL s^{-1} hen^{-1})
P_{litter} = CO_2 production by litter/manure on the floor (mL s^{-1})
P_{manure} = CO_2 production by manure (mL s^{-1})
P_{heater} = CO_2 production by heaters (mL s^{-1})
$[CO_2]_{in}$ = indoor CO_2 concentration (ppm)
$[CO_2]_{amb}$ = ambient CO_2 concentration (ppm).

$$P_{hen} = \frac{\mathrm{THP} \times \mathrm{RQ}}{16.18 + 5.02\mathrm{RQ}} \times M \tag{2}$$

where M is the body mass of the hen (kg).

For each sampling cycle in a day, the NH_3 emissions were calculated by multiplying the VR, the corresponding difference between indoor and ambient NH_3 concentrations, and the cycle interval (30 min). The emission data were then corrected to standard temperature and pressure condition. The daily NH_3 emission (ER) was the sum of the emission data of all cycles and was expressed as emissions per hen (eq. 3), per animal unit (1 AU = 500 kg live animal weight), or per kg eggs produced.

$$\mathrm{ER} = \sum \mathrm{VR} \times \left([\mathrm{NH_3}]_{in} - [\mathrm{NH_3}]_{amb}\right) \times 10^{-6} \times \frac{1800}{3600} \times \frac{w_m}{V_m} \times \frac{T_{std}}{T_{ab}} \times \frac{P_a}{P_{std}} \tag{3}$$

where

ER = emission rate (g d^{-1} hen^{-1})
$[NH_3]_{in}$ = indoor NH_3 concentration (ppm)
$[NH_3]_{amb}$ = ambient NH_3 concentration (ppm)
w_m = molar weight of NH_3 (17.031 g mol^{-1})
V_m = molar volume of NH_3 at standard temperature (0°C) and pressure (101.325 kPa) (0.0224 m^3 mol^{-1})
T_{std} = standard temperature (273.15 K)
T_{ab} = absolute house temperature (K)
P_{std} = standard barometric pressure (101.325 kPa)
P_a = atmospheric barometric pressure (acquired from the local weather station).

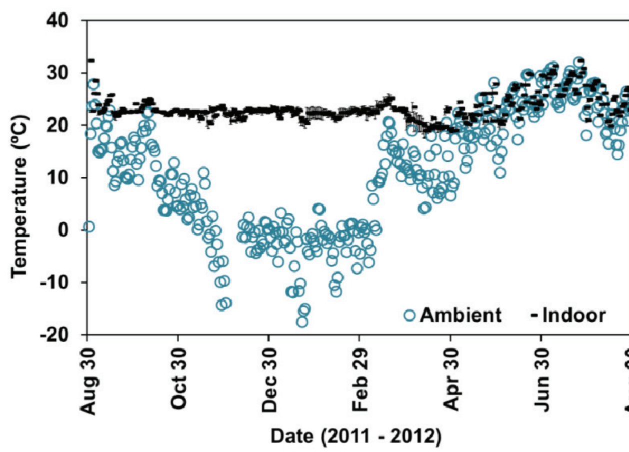
Statistical Analysis

All statistical analyses were performed using SAS 9.2 (SAS Institute, Inc., Cary, N.C.). Data from two PMUs in each house were averaged to represent the house-level concentration and emission data. Comparison of temperatures between different locations in the houses was performed using ANOVA procedure. Daily mean VR, indoor CO_2 and NH_3 concentrations, and NH_3 emissions of the four hen houses were pooled and fitted with either linear or quadratic models for the effect of ambient temperature. The effect of ambient temperature and manure accumulation on NH_3 emissions was tested using a multiple regression procedure with standardized regression coefficients.

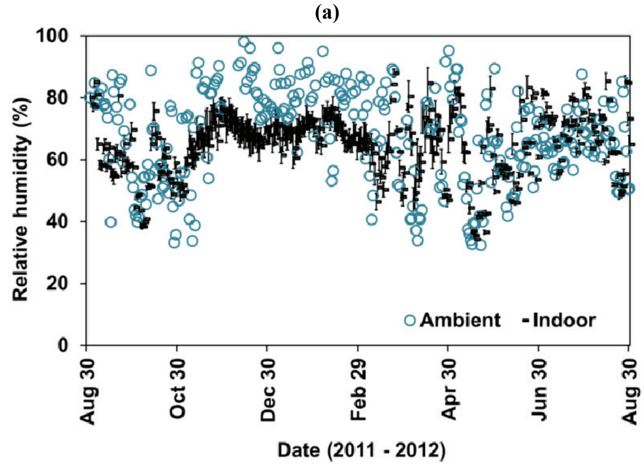
Results and Discussion

Thermal Environment

Daily indoor and ambient temperature and RH profiles are shown in figure 4. Indoor temperatures in the four houses were quite similar, as indicated by the small error bars (fig. 4a). There were several cold days in the winter of



(a)



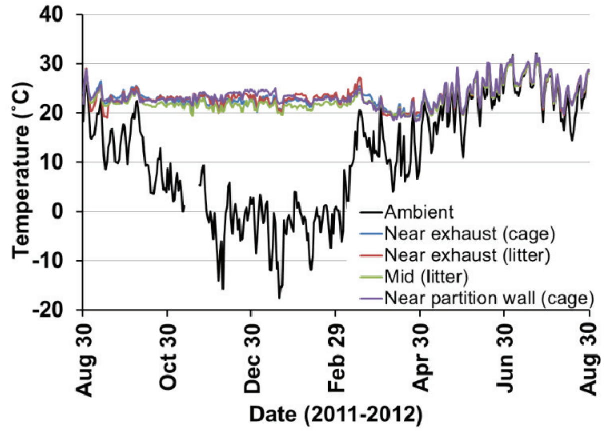
(b)

Figure 4. (a) Daily indoor and ambient temperature and (b) relative humidity (RH). The indoor data are means of four houses with standard errors; the ambient data are means of two measurements

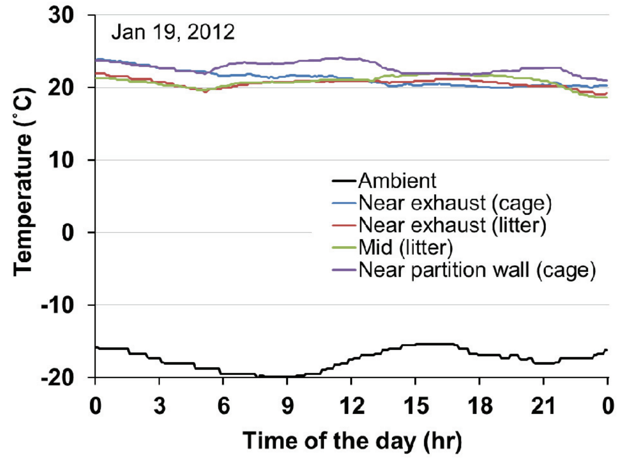
2011-2012. With supplemental heat, indoor temperatures of the hen houses were generally maintained above 20°C. The daily indoor temperatures increased in summer and were close to the ambient temperature, indicating that the ventilation system was well managed to remove the excess heat produced by the hens. The maximum daily average indoor temperature (31.5°C) was slightly lower than the outdoor temperature (32.0°C), presumably due to water evaporation inside the houses, hence the cooling effect. However, the outdoor air temperature could have been overestimated due to heat irradiation from the concrete floors in the vicinity of the temperature sensors. The mean daily indoor temperature was 23.4°C during the experimental period.

The indoor RH was relatively stable in winter (ranging from 57% to 79%, fig. 4b) but fluctuated considerably in summer (ranging from 31% to 88%, fig. 4b). This was presumably attributed to the higher VR in warmer weather, resulting in indoor RH being more affected by the variable ambient humidity. The mean daily indoor RH in the aviary houses was 64%, and the mean ambient RH was 68%.

Figure 5 shows the temperature distribution at four locations in the aviary houses. The daily mean temperatures at different locations were quite consistent (fig. 5a), and no significant differences were found among the locations (table 3). On a cold day (19 January 2012) of the monitoring period, the temperature near the partition wall was somewhat higher than at other locations (fig. 5b), especially when the ambient temperature was low. Although the mean temperatures were not significantly different among the locations (table 3), the temperature near the partition wall was significantly higher than at some other locations during the coldest period (7:30 a.m. to 9:30 a.m.), indicating some degree of non-uniform indoor temperature distribution. This outcome presumably resulted from short-circuiting of the incoming air (i.e., air entering the attic got exhausted before reaching the inlets near the partition wall). On a warm day (15 June 2012), temperatures at the different locations were comparable (fig. 5c). Zhao and Xin (2013) reported that incoming air was heated in the attic of aviary houses before entering the house in summer, which is attributable to solar heating of the non-roof-insulated attic space. Results of the current monitoring study confirmed warmer, albeit not significant, temperatures near the partition wall (table 3). It should be noted that a small temperature elevation (e.g., 1°C) during heat stress periods can cause much more detriment than during thermoneutrality. Therefore, attention should be paid to temperature and ventilation management near the partition wall.



(a)



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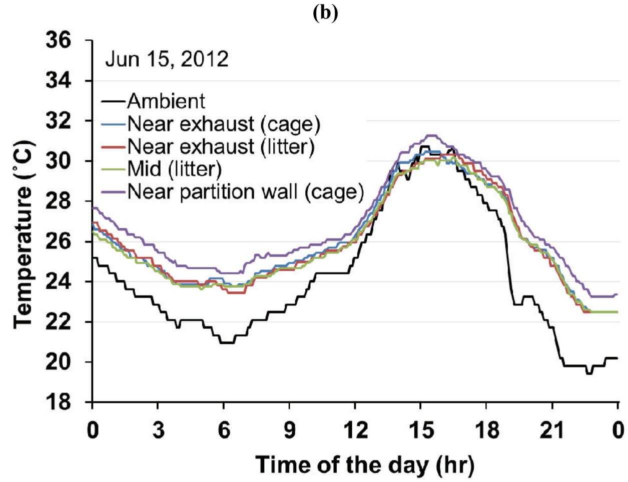


(c)

Figure 5. Temperatures at different locations in the aviary houses: (a) daily mean, (b) on a cold day, and (c) on a warm day. Data for "ambient" and "near exhaust (litter)" are means of temperatures in two houses; data for "near exhaust (cage)", "mid (litter)", and "near partition wall (cage)" are means of temperatures in four houses.

VENTILATION RATE (VR)

Daily VR and the relationship between VR and ambient temperature are shown in figure 6. The minimal VR of the hen houses was found to be 0.74 $m^3\ h^{-1}\ hen^{-1}$ in the winter, while the highest VR was around 11 $m^3\ h^{-1}\ hen^{-1}$ in the summer. We noticed a higher-than-the-baseline minimal VR on the coldest day, possibly due to the need for indoor air quality control. In all the hen houses, VR increased as ambient temperature (T_a) increased (fig. 6b) and leveled off upon reaching the maximum capacity. The VR and T_a relationship can be described with the following empirical models (eqs. 4, 5, and 6):

For $T_a \le 3°C$: $\quad$ VR = 0.77 $\quad$ (4)

For $3°C < T_a < 27°C$:

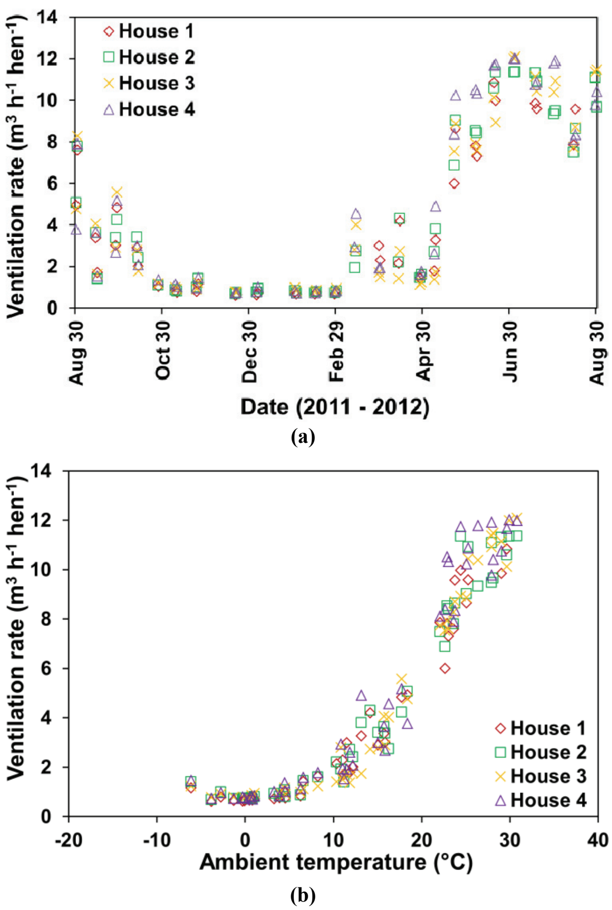
Table 3. Temperatures (°C) at four locations in the four houses.[a]

Location	Mean ±SD	Min.	Max.	
	Daily mean[b]			
In cage near exhaust	23.5 a ±1.0	19.2	31.4	
Above litter near exhaust	23.5 a ±0.7	18.6	31.3	
Above middle litter area	22.8 a ±1.1	18.7	31.2	
In cage near partition	23.6 a ±1.2	18.3	31.9	
Outside ambient	11.5 ±0.2	-17.6	32.0	
	Cold day[b] (19 January 2012)			Coldest period[c] (7:30 to 9:30)
In cage near exhaust	20.7 a ±1.3	17.5	26.3	20.6 AB ±1.3
Above litter near exhaust	20.6 a ±0.5	18.7	22.1	20.7 AB ±0.4
Above middle litter area	20.2 a ±1.6	16.4	23.6	20.1 B ±1.3
In cage near partition	21.9 a ±2.6	16.8	26.3	22.6 A ±2.1
Outside ambient	-17.6 ±0.1	-19.8	-15.4	-19.8 ±0.0
	Hot day[b] (15 June 2012)			Hottest period[c] (14:00 to 17:00)
In cage near exhaust	26.0 a ±0.5	22.5	30.4	30.2 A ±0.3
Above litter near exhaust	25.9 a ±0.2	22.5	30.3	30.0 A ±0.0
Above middle litter area	26.0 a ±0.7	22.5	30.2	30.1 A ±0.7
In cage near partition	26.6 a ±0.9	23.2	31.3	30.5 A ±0.9
Outside ambient	24.2 ±0.0	19.4	30.7	29.9 ±0.1

[a] Each datum is the mean, minimum, or maximum of four measurements (from four houses), except for "above litter near exhaust" and "ambient" data, which are the mean, minimum, or maximum of two measurements. SD = standard deviation.

[b] Means followed by different lowercase letters are significantly different ($p < 0.05$).

[c] Means followed by different uppercase letters are significantly different ($p < 0.05$).



(a)

(b)

Figure 6. (a) Daily mean ventilation rate (VR) during the experimental period, and (b) the relationship between VR and ambient temperature.

$$VR = 0.021T_a^{\ 2} - 0.166T_a + 1.309 \quad (5)$$

$$(R^2 = 0.95,\ p < 0.05)$$

For $T_a \geq 27°C$: $\quad VR = 11.0 \quad (6)$

CO_2 CONCENTRATIONS

There were clear seasonal (fig. 7a) and diurnal (fig. 8) variations in indoor CO_2 concentration. Indoor CO_2 concentrations rose on cooler hours/days and decreased on warmer hours/days. The daily CO_2 concentrations in the aviary houses were 1520 ±87 ppm, with a maximum of 3215 ppm in winter and a minimum of 452 ppm in summer (fig. 7b). The inverse relationship between indoor CO_2 concentration (in ppm) and T_a can be described with the following empirical models (eqs. 7, 8, and 9):

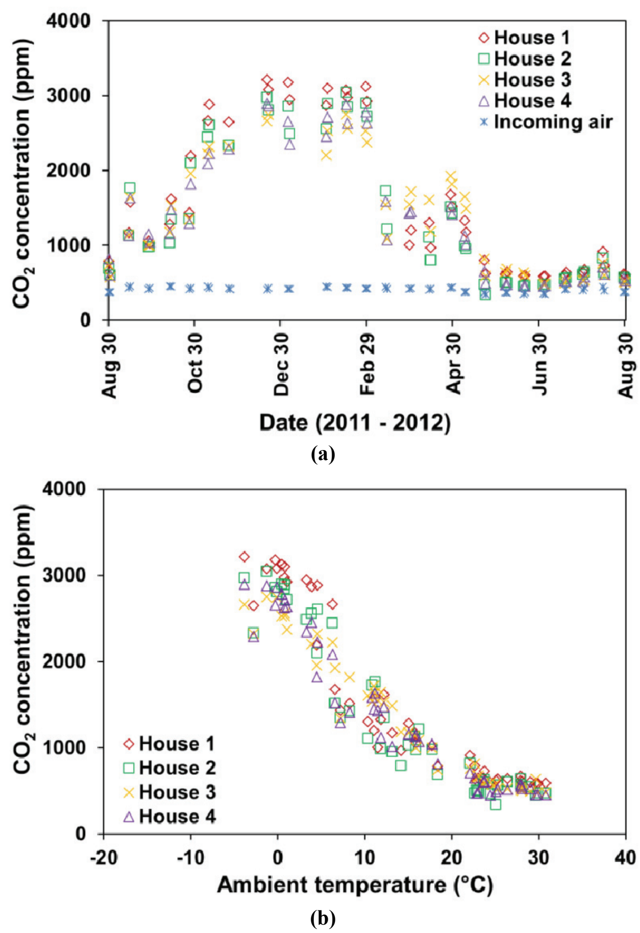
For $T_a \leq 3°C$: $\quad [CO_2]_{in} = 2783 \quad (7)$

For $3°C < T_a < 27°C$:

$$[CO_2]_{in} = 2.72T_a^{\ 2} - 160.04T_a + 2877.6 \quad (8)$$

$$(R^2 = 0.86,\ p < 0.05)$$

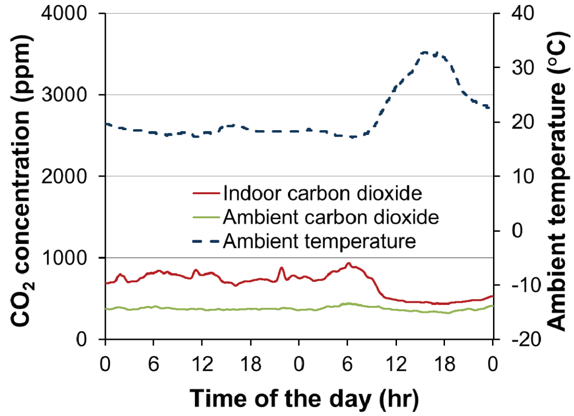
For $T_a \geq 27°C$: $\quad [CO_2]_{in} = 542 \quad (9)$



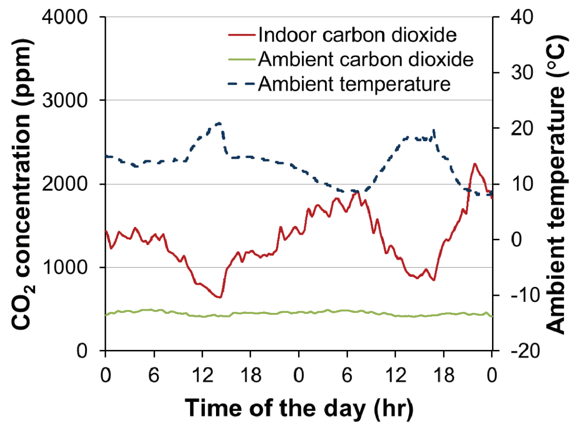
(a)

(b)

Figure 7. (a) Daily indoor and ambient carbon dioxide (CO_2) concentrations, and (b) relationship between indoor CO_2 concentration and ambient temperature. The CO_2 concentration values for incoming air are means of the four hen houses.



(a)



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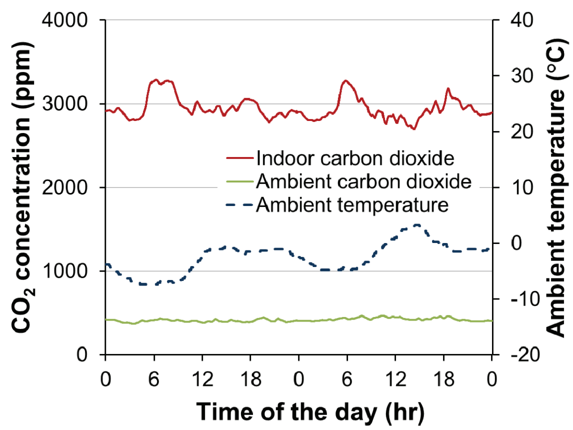
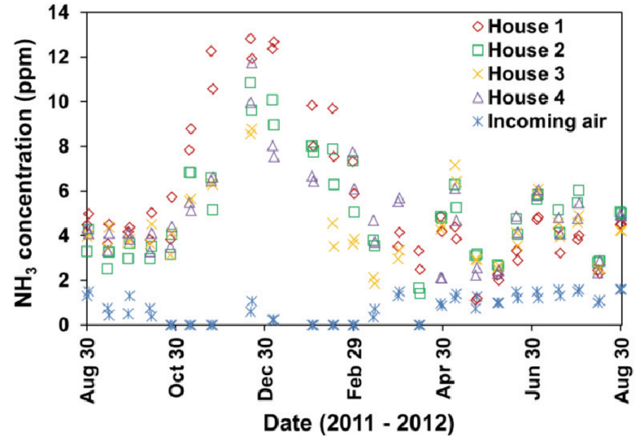


(c)

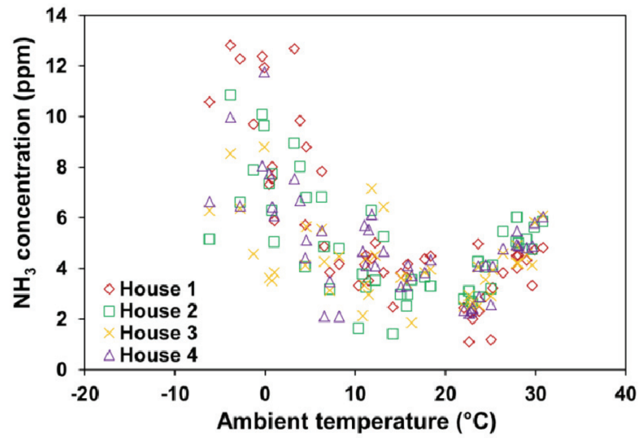
Figure 8. Diurnal variation (two consecutive days) of indoor and ambient carbon dioxide (CO_2) concentrations on (a) hot (29-30 Aug. 2011), (b) mild (19-20 Oct. 2011), and (c) cold (20-21 Dec. 2011) days. The CO_2 concentration values are means of the four hen houses.

NH_3 Concentrations and Emissions

Daily mean indoor and ambient NH_3 concentrations are delineated in figure 9a. The indoor NH_3 concentrations peaked in late autumn and winter due to the reduced VR but stayed relatively stable for the rest of the one-year measurement period. The average indoor NH_3 concentration of the four houses was 5.2 ppm. The maximum NH_3 concentration was 12.8 ppm for daily mean, and 19.6 ppm within a winter day; both were below the 25 ppm threshold recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) and the National Institute for Occupational Safety and Health (NIOSH). The NH_3 concentrations found in this study were lower than those reported in previous European studies (table 1) and in similar aviary houses with brown birds in the U.S. (Hayes et al., 2013b). The result could be attributed to better management of the manure and litter floor access at this farm. Firstly, the manure on belts in the hen houses was continuously dried with recirculated indoor air, which presumably reduced the NH_3 volatilization by reducing the decomposition rate of uric acid and urea (Brinson et al., 1994; Molloy and Tunney, 1983; Schefferle, 1965). Secondly, the manure on belts was removed from the hen houses more frequently (1/3 each day) as compared to the manure removal in other studies, e.g., one time per week (Nimmermark et al., 2009). Thirdly, the hens were allowed to stay on the litter floor throughout the day in some European systems; in contrast, the hens in this study were given 9.75 h litter floor access each day, thus reducing the amount of manure deposition on the litter floor and thus ammonia volatilization. It should be noted that the higher indoor NH_3 concentration is associated with minimum VR in cold weather. There were several cold days when T_a was below -10°C (fig. 4a) in the winter of 2011-2012. However,



(a)



(b)

Figure 9. (a) Daily mean indoor and ambient ammonia (NH_3) concentrations, and (b) relationship between indoor NH_3 concentration and ambient temperature. The NH_3 concentration values for incoming air are means of the four hen houses.

the NH_3 concentrations on those days were not monitored due to the bi-weekly measurement schedule.

Part of the eave inlet air was affected by the exhaust air due to the proximity between the two (fig. 1a). As a result, some NH_3 was circulated back to the hen house. As shown in figure 9a, NH_3 gas was occasionally detected at the air inlet of the hen houses, but its concentration (<2 ppm) was significantly lower than the indoor levels.

Indoor NH_3 concentration steadily decreased as T_a increased until 23°C (fig. 9b), resulting from the increasing VR. Interestingly, this trend began to reverse when T_a exceeded 23°C. This outcome was presumably attributed to increased NH_3 volatilization from manure at higher air temperature (Pereira et al., 2012; Sommer et al., 1991) while VR was approaching its maximum. The following quadratic model (eq. 10) was fitted to delineate this relationship:

$$[NH_3]_{in} = 7.4 - 0.4T_a + 0.01T_a^2 \tag{10}$$

$$(R^2 = 0.52, p < 0.05)$$

Diurnal variations of indoor NH_3 concentrations under three weather conditions (hot, mild, and cold) are shown in figure 10. Generally, NH_3 concentrations were lower in mid-day but higher at night due to varying VR under hot and mild weather conditions but remained relatively high all day under cold climate (fig. 10).

Figure 11 shows daily NH_3 emissions of the four aviary houses. The emissions showed some degree of fluctuation throughout the year (fig. 11a). The following quadratic model (eq. 11) shows that the NH_3 emissions (in g d^{-1} hen^{-1}) were somewhat associated with T_a (fig. 11b):

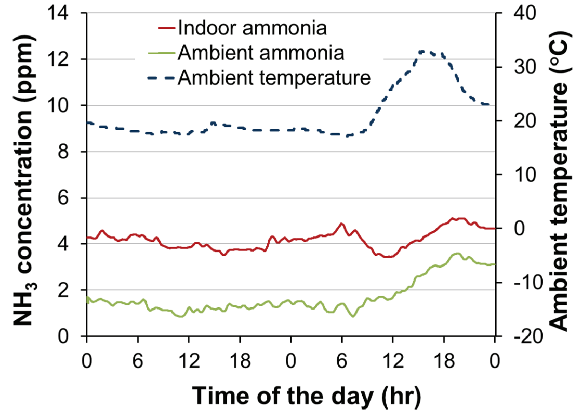
$$ER = 0.123 - 0.00136T_a + 0.00012T_a^2 \tag{11}$$

$$(R^2 = 0.23, p < 0.05)$$

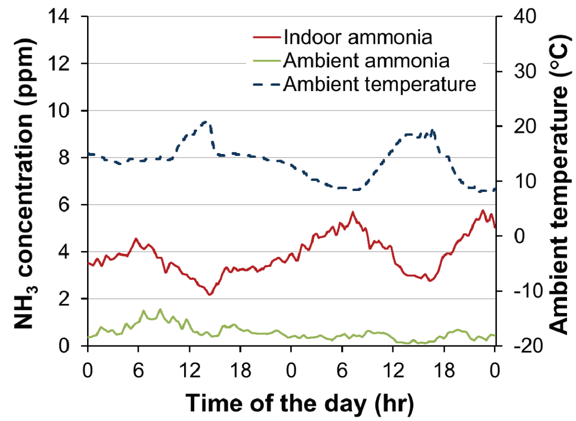
The elevated NH_3 emission at low T_a was speculated to result from higher indoor RH and thus higher moisture content of the litter/manure, which favored NH_3 volatilization (Groot Koerkamp et al., 1998b). The elevated NH_3 emission at higher T_a was probably the result of increased NH_3 volatilization due to faster conversion of uric acid by microbes and high VR (fig. 6b) in warm weather (Groot Koerkamp et al., 1998b; Aarnink and Elzing, 1998).

Higher NH_3 emission may also be associated with manure accumulation time (MAT) on the floor. To examine this effect, multiple-variable regression was performed with emission rate as the dependent variable and T_a and MAT (using hen age as substitute input) as independent variables. The regression coefficients were standardized (i.e., expressed as the effect of one SD change, as opposed to a unit change in independent variables to dependent variable); thus, the relative importance of T_a and MAT to NH_3 emission could be compared. Table 4 shows that both MAT and T_a positively affected NH_3 emission, while the impact of T_a (standardized coefficient = 0.62) was more pronounced as compared to MAT (standardized coefficient = 0.38).

Ammonia emissions from the four aviary hen houses ranged from 0.05 to 0.30 g d^{-1} hen^{-1} (or 15.1 to 98.6 g d^{-1} AU^{-1}, 0.9 to 6.0 g d^{-1} [kg egg]$^{-1}$), with a mean of 0.14 g d^{-1} hen^{-1} (or 44.5 g d^{-1} AU^{-1}, 2.8 g d^{-1} [kg egg]$^{-1}$). These values are in the range of 0.02 to 0.78 g d^{-1} hen^{-1} (table 1) reported in the literature, albeit on the low side for the reasons stated earlier. The magnitude of NH_3 emissions found in this study was quite consistent with the value (0.15 g d^{-1} hen^{-1}) that was measured in similar aviary houses containing Hy-Line brown hens in central Iowa (Hayes et al., 2013b).



(a)



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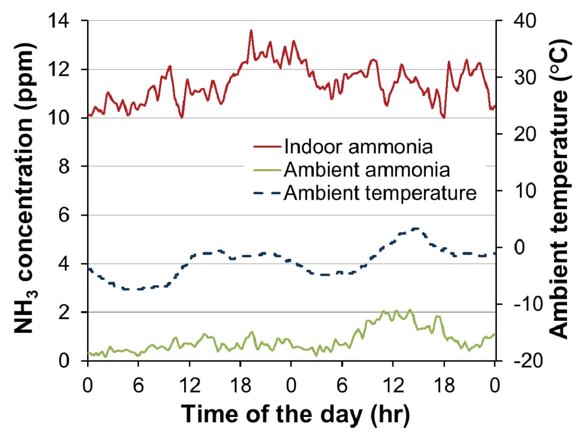

(c)

Figure 10. Diurnal variations (two consecutive days) of indoor and ambient ammonia (NH_3) concentrations on (a) hot (29-30 Aug. 2011), (b) mild (19-20 Oct. 2011), and (c) cold (20-21 Dec. 2011) days. The NH_3 concentration values are means of the four hen houses.

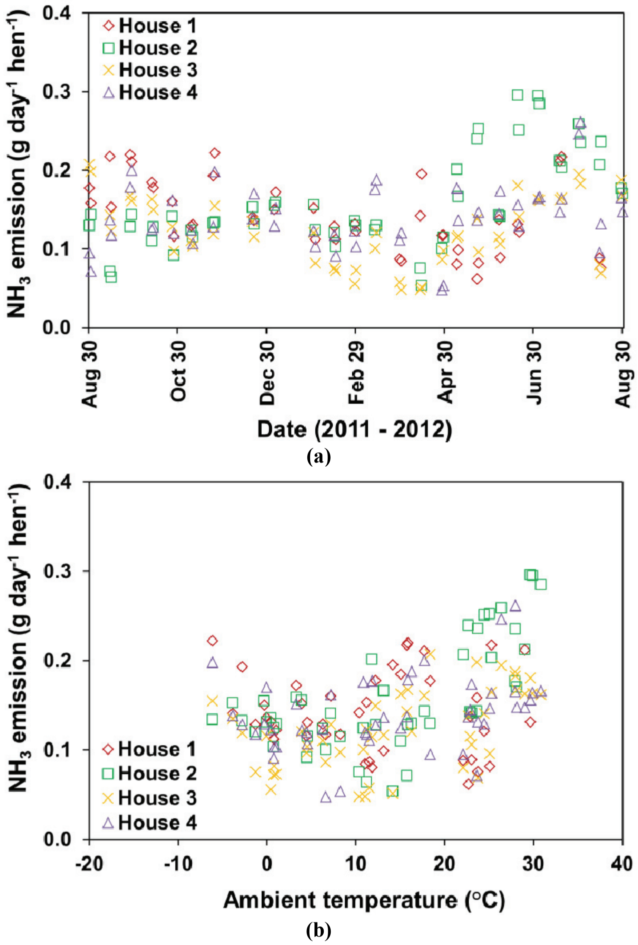

Figure 11. (a) Daily ammonia (NH_3) emissions throughout the year, and (b) relationship between NH_3 emission and ambient temperature.

A summary of NH_3 concentrations and emissions, together with the thermal environment and VR found in this study, is presented in table 5. It should be noted that all the data reported in this study were obtained from four aviary houses located on the same commercial farm. Extrapolation of these data to other farms with different management (e.g., manure removal frequency, use or absence of the manure-drying system, ventilation system management, etc.) should be done with care.

Table 4. Results from multiple regression (adjusted R^2 = 0.27, p < 0.05) for effect of ambient temperature (T_a) and manure accumulation time (MAT) on ammonia emission.

	Coefficient	Standard Error	p-Value	Standardized Coefficient
Intercept	67.05	10.81	<0.001	-
T_a	0.93	0.18	<0.001	0.62
MAT	2.49	0.29	<0.001	0.38

Aviary versus Other Housing Systems

Manure-belt and high-rise cage systems remain the two most popular housing systems for laying hens in the U.S. Liang et al. (2005) reported NH_3 concentrations to be 3 to 5 ppm in two U.S. manure-belt hen houses, but 36 to 45 ppm in two U.S. high-rise hen houses. The NH_3 concentrations of the aviary houses in this study (5 ppm) were in line with those of the manure-belt houses. However, it is worth noting that the stocking density of the aviary houses was much lower than that of the manure-belt houses. The NH_3 concentrations of the aviary houses were lower than those of the high-rise houses. The NH_3 emissions from manure-belt houses ranged from 0.05 to 0.18 g d^{-1} hen^{-1} (Groot Koerkamp et al., 1998a; Liang et al., 2005), which was significantly lower than that from high-rise houses (0.83 to 1.57 g d^{-1} hen^{-1}) (Keener et al., 2002; Liang et al., 2005; Li et al., 2012; Lin et al., 2012). Again, NH_3 emissions from the aviary houses in this study were within the range of those for manure-belt houses.

Summary and Conclusions

Ammonia (NH_3) concentrations and emissions of four commercial aviary houses with 50,000 white laying hens per house in central Iowa were monitored bi-weekly for two consecutive days over a one-year period. Carbon dioxide (CO_2) concentrations of the inlet and exhaust air of the houses were monitored and used to estimate building ventilation rate (VR) along with literature values on metabolic rates of the hens. Ambient and indoor air

Table 5. Summary of the thermal environment, ventilation rate (VR), carbon dioxide (CO_2) concentration, ammonia (NH_3) concentration, and NH_3 emission in the four aviary houses.

Variables	Unit	Mean ±SD[a]	Min. Daily Mean / Within-Day Min.[b]	Max. Daily Mean / Within-Day Max.[c]
Ambient temperature	°C	11.5 ±0.2	-17.6/-26.1	32.0/42.3
Ambient RH	%	68 ±3	32/23	95/98
Indoor temperature	°C	23.4 ±0.3	17.5/16.7	31.5/37.5
Indoor RH	%	64 ±3	31/23	88/95
VR	m^3 h^{-1} hen^{-1}	4.5 ±0.6	0.7/0.5	12.0/12.2
Ambient CO_2 concentration	ppm	409 ±26	368/341	530/563
Ambient NH_3 concentration	ppm	1.2 ±0.2	-[d]/-[d]	2.1/3.8
Indoor CO_2 concentration	ppm	1520 ±87	452/437	3215/3819
Indoor NH_3 concentration	ppm	5.2 ±0.5	-[d]/-[d]	12.8/19.6
NH_3 emission	g d^{-1} hen^{-1}	0.14 ±0.01	0.05/-	0.30/-
	g d^{-1} AU^{-1}	44.5 ±1.9	15.1/-	98.6/-
	g d^{-1} [kg egg]$^{-1}$	2.8 ±0.3	0.9/-	6.0/-

[a] Each datum is the mean of four values (four hen houses) except for the ambient temperature and RH, which are mean of two values (two HOBO sensors). SD = standard deviation.
[b] Each datum is the minimal value in one of the four houses, or at one of the two ambient measurement locations.
[c] Each datum is the maximal value in one of the four houses, or at one of the two ambient measurement locations.
[d] Below detection capacity (2 ppm).

temperature and RH were continuously measured throughout the one-year period. The following observations and conclusions were made:

- Daily indoor temperature and RH averaged 23.4°C ±0.3°C and 64% ±3%, respectively. Care should be taken to ensure proper distribution of fresh air near the partition wall of the double-wide hen building. With three 73.25 kW supplemental heaters in each house, the indoor temperature could be readily maintained above 20°C in winter.
- Daily indoor CO_2 concentration averaged 1520 ±87 ppm. The maximum CO_2 concentration within a day was 3819 ppm in winter. The estimated mean VR was 4.5 ±0.6 $m^3\ h^{-1}\ hen^{-1}$, ranging from a minimum of 0.74 $m^3\ h^{-1}\ hen^{-1}$ to a maximum of 12.2 $m^3\ h^{-1}\ hen^{-1}$.
- Daily indoor NH_3 concentration averaged at 5.2 ±0.5 ppm. The highest NH_3 concentration was 12.8 ppm for the daily mean and 19.6 ppm within the day. The NH_3 concentration showed significant seasonal and diurnal variations.
- Daily mean NH_3 emission was 0.14 ±0.01 g $d^{-1}\ hen^{-1}$. This value was somewhat lower than the literature value reported for European aviary housing systems but was consistent with the value reported for similar aviary houses with brown hens in the Midwestern U.S.
- The NH_3 concentrations and emissions of the aviary houses were comparable to those of manure-belt cage houses but much lower than those of high-rise cage houses.

Acknowledgements

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References

Aarnink, A. J. A., and A. Elzing. 1998. Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs. *Livestock Prod. Sci.* 53(2): 153-169.

Asman, W. A. H., M. A. Sutton, and J. K. Schjørring. 1998. Ammonia: Emission, atmospheric transport and deposition. *New Phytol.* 139(1): 27-48.

Brinson, S. E., M. L. Cabiera, and S. C. Tyson. 1994. Ammonia volatilization from surface-applied, fresh, and composted poultry litter. *Plant Soil* 167(2): 213-218.

Chepete, H. J., H. Xin, M. C. Puma, and R. S. Gates. 2004. Heat and moisture production of poultry and their housing systems: Pullets and layers. *ASHRAE Trans.* 110(2): 286-299.

Crook, B., J. F. Robertson, S. A. Glass, E. M. Botheroyd, J. Lacey, and M. D. Topping. 1991. Airborne dust, ammonia, microorganisms, and antigens in pig confinement houses and the respiratory health of exposed farm workers. *American Ind. Hyg. Assoc. J.* 52(7): 271-279.

Deaton, J. W., F. N. Reece, and Lott. B. D. 1984. Effect of atmospheric ammonia on pullets at point of lay. *Poultry Sci.* 63(2): 384-385.

Dekker, S. E. M., A. J. A. Aarnink, I. J. M. de Boer, and P. W. G. Groot Koerkamp. 2011. Emissions of ammonia, nitrous oxide, and methane from aviaries with organic laying hen husbandry. *Biosyst. Eng.* 110(2): 123-133.

Groot Koerkamp, P. W. G. 1995. The effect of manure and litter handling and indoor climatic conditions on ammonia emissions from a battery cage and an aviary housing system for laying hens. *Netherlands J. Agric. Sci.* 43(4): 351-373.

Groot Koerkamp, P. W. G., and R. Bleijenberg. 1998. Effect of type of aviary, manure, and litter handling on the emission kinetics of ammonia from layer houses. *British Poultry Sci.* 39(3): 379-392.

Groot Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. P. White, J. Hartung, J. Seedorf, M. Schröder, K. H. Linkert, S. Pedersen, H. Takai, J. O. Johnsen, and C. M. Wathes. 1998a. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 79-95.

Groot Koerkamp, P. W. G., L. Speelman, and J. H. M. Metz. 1998b. Litter composition and ammonia emission in aviary houses for laying hens: Part 1. Performance of a litter drying system. *J. Agric. Eng. Res.* 70(4): 375-382.

Harper, L. A., T. K. Flesch, J. M. Powell, W. K. Coblentz, W. E. Jokela, and N. P. Martin. 2009. Ammonia emissions from dairy production in Wisconsin. *J. Dairy Sci.* 92(5): 2326-2337.

Hayes, M. D., H. Xin, H. Li, T. A. Shepherd, Y. Zhao, and J. P. Stinn. 2013a. Heat and moisture production of Hy-Line brown hens in aviary houses in the Midwestern U.S. *Trans. ASABE* 56(2): 747-752.

Hayes, M. D., H. Xin, H. Li, T. A. Shepherd, Y. Zhao, and J. P. Stinn. 2013b. Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern U.S. *Trans. ASABE* (in review).

Jacobson, L., B. Hetchler, N. Akdeniz, S. Hoff, A. J. Heber, J. Q. Ni, Y. Zhang, and J. Koziel. 2011. Air pollutant emissions from confined animal buildings (APECAB) project summary. St. Joseph, Mich.: ASABE.

Keener, H. M., D. L. Elwell, and D. Grande. 2002. NH_3 emissions and N-balances for a 1.6 million caged layer facility: Manure belt/composting vs. deep pit operation. *Trans. ASAE* 45(6): 1977-1984.

Li, H., H. Xin, Y. Liang, R. S. Gates, E. F. Wheeler, and A. Heber. 2005. Comparison of direct vs. indirect ventilation rate determinations in layer barns using manure belts. *Trans. ASAE* 48(1): 367-372.

Li, H., H. Xin, R. T. Burns, L. D. Jacobson, S. Noll, S. J. Hoff, J. D. Harmon, J. A. Koziel, I. Celen, and B. Hetchler. 2011. Air emissions from tom and hen turkey houses in the U.S. Midwest. *Trans. ASABE* 54(1): 305-314.

Li, H., H. Xin, R. T. Burns, S.A. Roberts, S. Li, J. Kliebenstein, and K. Bregendahl. 2012. Reducing ammonia emissions from high-rise laying-hen houses through dietary manipulation. *J. Air Waste Mgmt. Assoc*. 62(2): 160-169.

Liang, Y., H. Xin, E. F. Wheeler, R. S. Gates, H. Li, J. S. Zajaczkowski, P. A. Topper, K. D. Casey, B. R. Behrends, and D. J. Burnham. 2005. Ammonia emissions from U.S. laying hen houses in Iowa and Pennsylvania. *Trans. ASAE* 48(5): 1927-1941.

Lin, X. J., E. L. Cortus, R. Zhang, S. Jiang, and A. J. Heber. 2012. Ammonia, hydrogen sulfide, carbon dioxide, and particulate matter emissions from California high-rise layer houses. *Atmos. Environ.* 46(1): 81-91.

Molloy, S. P., and H. Tunney. 1983. A laboratory study of ammonia volatilization from cattle and pig slurry. *Irish J. Agric. Food Res.* 22(1): 37-45.

Moore, P. A., D. Miles, R. Burns, D. Pote, K. Berg, and I. H. Choi.

2011. Ammonia emission factors from broiler litter in barns, in storage, and after land application. *J. Environ. Qual.* 40(5): 1395-1404.
Mosquera, J., K. Groenestein, N. W. M. Ogink, and A. J. A. Aarnink. 2012. Evaluation of the CO_2 mass balance method to calculate ventilation rates from mechanically ventilated livestock buildings. Paper No. ILES12-0476. St. Joseph, Mich.: ASABE.
Ni, J. Q., A. J. Heber, T. T. Lim, P. C. Tao, and A. M. Schmidt. 2008. Methane and carbon dioxide emission from two pig finishing barns. *J. Environ. Qual.* 37(6): 2001-2011.
Ning, X. 2008. Feeding, defecation, and gaseous emission dynamics of W-36 laying hens. PhD diss. Ames, Iowa: Iowa State University.
Nimmermark, S., V. Lund, G. Gustafsson, and W. Eduard. 2009. Ammonia, dust, and bacteria in welfare-oriented systems for laying hens. *Ann. Agric. Environ. Med.* 16(1): 103-113.
Pereira, J., T. H. Misselbrook, D. R. Chadwick, J. Coutinho, and H. Trindade. 2012. Effects of temperature and dairy cattle excreta characteristics on potential ammonia and greenhouse gas emissions from housing: A laboratory study. *Biosyst. Eng.* 112(2): 138-150.
Schefferle, H. E. 1965. The decomposition of uric acid in built-up poultry litter. *J. Appl. Microbiol.* 28(3): 412-420.
Sommer, S. G., J. E. Olesen, and B. T. Christensen. 1991. Effects of temperature, wind speed, and air humidity on ammonia volatilization from surface applied cattle slurry. *J. Agric. Sci.* 117(1): 91-100.
Stinn, J. P., H. Xin, T. A. Shepherd, H. Li, and R. Burns. 2012. Ammonia and greenhouse gas emissions of a swine breeding-gestation-farrowing facility in the Midwestern USA. Paper No. ILES12-1014. St. Joseph, Mich.: ASABE.
USEPA. 2004a. Estimating ammonia emissions from anthropogenic nonagricultural sources. Draft final report. Washington, D.C.: U.S. Environmental Protection Agency
USEPA. 2004b. National emission inventory: Ammonia emissions from animal husbandry. Revised draft report. Washington, D.C.: U.S. Environmental Protection Agency.
Wheeler, E. F., K. D. Casey, R. S. Gates, H. Xin, J. L. Zajaczkowski, P. A. Topper, Y. Liang, and A. J. Pescatore. 2006. Ammonia emissions from twelve U.S. broiler chicken houses. *Trans. ASABE* 49(5): 1495-1512.
Winter, T., S. Linke, and T. Hinz. 2009. Farmers' exposure to ammonia in new systems of laying hens. In *Proc. 14th Intl. Congress of the International Society for Animal Hygiene (ISAH)*, 605-608. Brno, Czech Republic: Tribun EU.
Xin, H., Y. Liang, A. Tanaka, R. S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Q. Ni, and H. Li. 2003. Ammonia emissions from U.S. poultry houses: Part I. Measurement system and techniques. In *Proc. 3rd Intl. Conference on Air Pollution from Agricultural Operations*, 106-115. St. Joseph, Mich.: ASABE.
Xin, H., R. S. Gates, A. R. Green, F. M. Mitloehner, P. A. Moore Jr., and C. M. Wathes. 2011. Environmental impacts and sustainability of egg production systems. *Poultry Sci.* 90(1): 263-277.
Zhao, Y., and H. Xin. 2013. Roof insulation in laying-hen houses to ease summer heat. *Animal Industry Report* AS659, ASL R2803. Ames, Iowa: Iowa State University. Available at: http://lib.dr.iastate.edu/ans_air/vol659/iss1/54.
Zhao, Y., H. Xin, T. A. Shepherd, M. D. Hayes, and J. P. Stinn. 2013. Modeling ventilation rate, balance temperature, and supplemental heat need in alternative vs. conventional laying-hen housing systems. *Biosyst. Eng.* 115(3): 311-323.